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Radioactivity Associated with Geothermal Waters in the Western United States. A Modeling Effort to Calculate Working Levels of Radon-222 and Its Progeny for Nonelectrical Applications

Office of Radiation Programs, Las Vegas, Nev.

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A model is developed to calculate the working levels from the heat load requirements that are necessary to maintain interior conditions during winter climatic conditions when space heating is at its highest. Calculations were also included for an indoor pool facility which is partially heated by the heat loss of the pool water. The results show that the pool represents the highest potential exposure environment. Other applications that were included in this analysis included greenhouses, private dwellings, and apartment and motel complexes.

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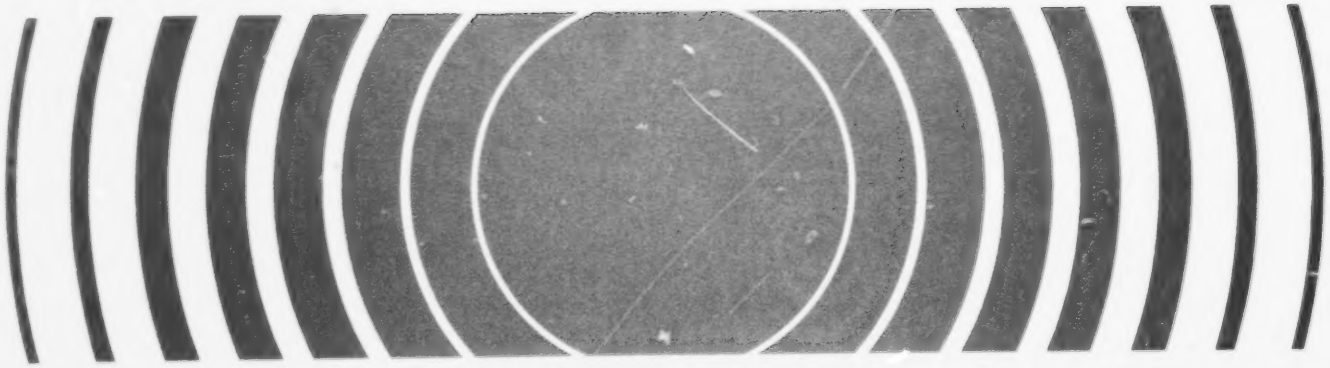

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RADIOACTIVITY ASSOCIATED WITH GEOTHERMAL WATERS IN THE WESTERN UNITED STATES

A Modeling Effort to Calculate Working Levels of Radon-222 and its Progeny for Nonelectrical Applications

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April 1978

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PREFACE

The Office of Radiation Programs of the U.S. Environmental Protection Agency has the responsibility to evaluate population exposure from ionizing and nonionizing radiation. This role is important in the development of Federal radiation protection philosophies, policies and controls.

Within the Office of Radiation Programs, the Las Vegas Facility (ORP-LVF) conducts detailed technical assessments of various radiation sources (e.g., nuclear fuel cycle facilities, and mineral and energy sources). These studies are supported by field studies to enhance the data base and to verify models of population exposure.

This report is the second of two reports which describe and summarize initial investigations conducted by ORP-LVF of the radioactivity associated with geothermal waters. The previous report presented the analytical results of the field study efforts. The present report describes a preliminary dose assessment of the current nonelectrical uses of shallow geothermal waters. This assessment will be used to determine the need for further in situ measurements. Comments or suggestions are invited from the readers.

Donald W Hendricks

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Director, Office of
Radiation Programs, LVF

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ABSTRACT

It has been known for some time that geothermal fluids contain a variety of dissolved minerals including radioactive species, particularly radium-226 and radon-222 There is an interest in examining radiation exposures to humans in contact with these fluids or their deposited minerals. The literature contains a few studies which have evaluated the ingestion and inhalation of radon and its daughters in situations associated with the balneological uses of thermal fluids. In this report, an attempt is made to predict the radon progeny (working levels) concentrations that could be expected inside structures using geothermal fluids for domestic hot water and space heating purposes.

A model is developed to calculate the working levels from the heat load requirements that are necessary to maintain interior conditions during winter climatic conditions when space heating is at its highest. Calculations were also included for an indoor pool facility which is partially heated by the heat loss of the pool water. The results show that the pool represents the highest potential exposure environment. Other applications that were included in this analysis included greenhouses, private dwellings, and apartment and motel complexes.

INTRODUCTION

In March 1976, the Office of Radiation Programs Las Vegas Facility, issued a report entitled "Radioactivity Associated with Geothermal Waters in the Western United States, Basic Data." Presented therein were radiochemical data on water samples collected from nearly 140 hot springs and shallow hot water wells. During the planning stages of the previously reported field survey, it was recognized that an accompanying assessment of public health implications resulting from radiation exposure from dissolved radon-222 would be desirable. Nonelectrical applications are of particular interest since they are currently the dominant use of geothermal resources and have recently received additional impetus from the Department of Energy (formerly the U.S. Energy Research and Development Administration) through resource assessment and development projects in Northern California and Idaho.

Nonelectrical applications of geothermal resources are not only widespread but also thriving (Peterson, 1976). These various applications are located in geographical areas where the potential of developing a geothermal area is enhanced by obvious natural emanations of the resource, i.e., hot pools, springs or fumaroles. Historically, mineral baths and similar enterprises represent the primary use of this resource. Present recreational and therapeutic uses are characterized by "health" resorts, hotels, motels, recreational vehicle parks, campgrounds, swimming pools and "plunges," bottled mineral water producers, picnic grounds, Federal (also State, county and city) parks, bath houses and spas, hospitals and summer camps (Peterson, 1976).

Additional uses have been proposed and/or developed over the past 20 years which include residential and commercial or industrial applications of geothermal energy. These developments have included extensive residential space heating projects in Boise, Idaho; Klamath Falls, Oregon; and Reno, Nevada. Also there are geothermally heated agricultural and aquaculture projects in California, Oregon and Colorado.

The additional impetus by the ERDA loan quarantee program has moved project proposals into reality. For example, an onion dehydration plant at Brady Hot Springs, Nevada and an expanded district space heating project in Boise, Idaho.

At the present time, there appear to be no major technological drawbacks to the utilization of a geothermal resource as a supplement or replacement of other energy forms (in areas where the resource is available). Processes such as refrigeration, air conditioning, cooking, drying and chemical processing can be assisted or replaced by geothermal energy (Reistad, 1975). Significant limitations do exist for applications in some areas, however, and include: low temperature, chemical composition, reservoir production capability, waste water disposal, and location of the resource with respect to the desired location of use or application.

In this report, we have limited the discussion to low-temperature geothermal applications (below boiling temperatures at the ground surface) and to uses that were observed during the sample collection of 1974. Five space heating applications were found to be prevalent and have the greatest potential for development in the future. Other applications, specifically commercial space heating and process hot water uses, are not discussed because these applications were not observed during the 1974 survey. Also, it is believed that the calculated working levels should be verified using existing structures. In this report a

methodology is developed to compute working levels based upon the space heating and domestic hot water requirements for a private residence, a motel, an apartment building, a greenhouse, and an indoor swimming pool.

The methodology uses the heat load requirements for these five applications to identify the demand on a geothermal system, measured by flow rate (liters per hour). The radon escaping from the heating system was assumed to be a percentage of the total quantity of radon passing through the system. Also included are domestic hot water uses which were assumed to release 100% of the dissolved radon during the time of use. Estimated working levels reported herein have not been verified at this time. Indoor air measurements should, at a later date, be conducted to provide verification.

THE CONCEPTUAL MODEL

Insofar as it is known, radon and radon daughter concentrations inside structures utilizing geothermal energy for space heating or domestic purpose have not been measured. Pohl-Rüling and Scheminzky (1972) found radon activities in air at the Badgastein spa in Austria to vary from 500 to 8000 picocuries per liter (pCi/l). The Austrian study did not provide a correlation between dissolved radon concentrations in water and concentrations in air. However, the authors felt barometric pressure played an important role. It was estimated that 200 millicuries of radon per day are released from the water at this spa: partly at the source, partly at the spills into reservoirs, and, finally, in the treatment baths (Pohl-Rüling and Scheminzky, 1972).

A model was developed to calculate the airborne concentration of radon and radon progeny as a function of building heat load requirements in conjunction with a mass balance concept to describe radon gas buildup and loss within the structures. This model is depicted in Figure 1. There are three steps in the computations as shown in the figure.

The first step is to calculate the required heat, in British Thermal Units (BTU) to maintain interior design conditions for a specific winter environment. This is accomplished using the National Bureau of Standards Load Determination program (NBSLD) for computing heating and cooling loads in buildings (Kusuda, 1976).

For step two, the radon input rate is calculated assuming that the required heat is provided by a geothermal source, that the heat exchange efficiency is predetermined, and that the

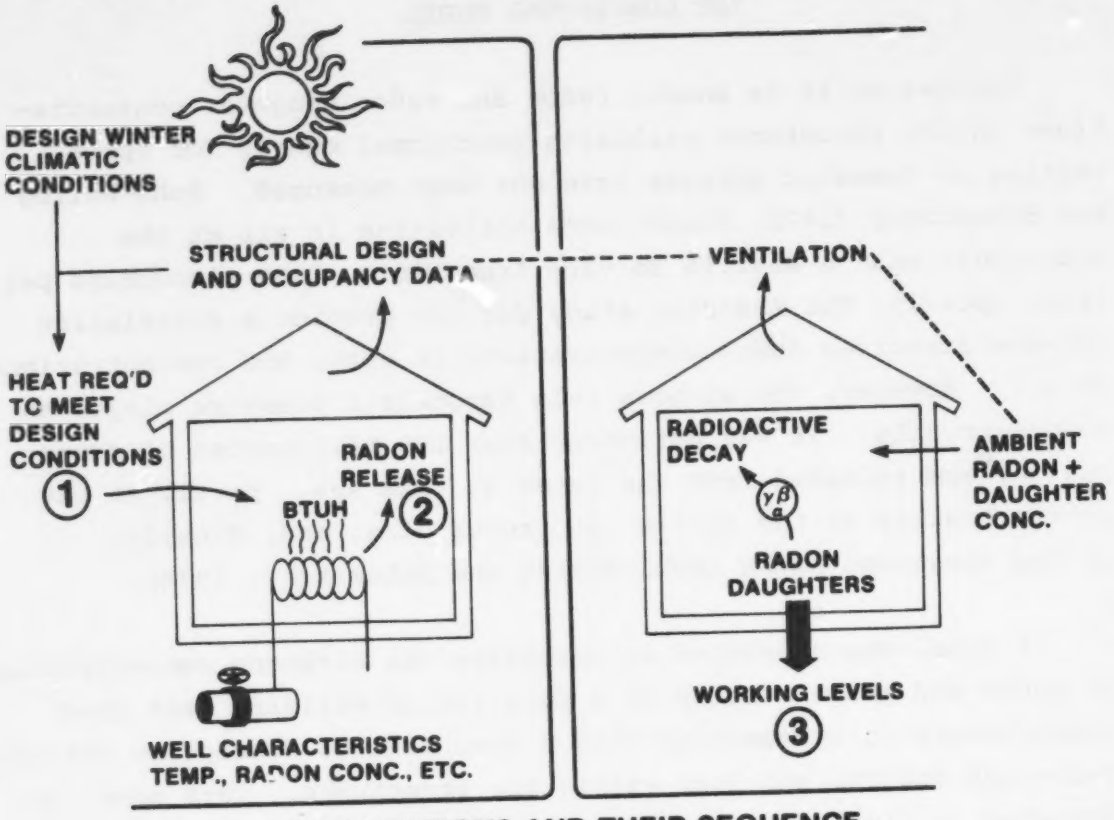

Figure 1. Conceptual model to calculate working levels based upon radon released from a space heating system

release fraction of radon from the heat exchangers is known. Radon release fraction into the room was estimated to be one percent (1%) of the total radon flowing through the system. Radon is expected to be released within these design structures because it has been reported that hydrogen sulphide, another dissolved gas species, was detectable inside geothermally heated homes in Boise, Idaho. Actual radon or radon progeny data are not available to accurately estimate this "partition factor." Potential multiple sources such as leakage around pipe fittings, valves and vented surge tanks can and probably exist.

For domestic uses and pools, the degassed radon is assumed to be totally released into the surrounding air and to be distributed equally throughout the structure.

In the case where geothermal water is used for both heating and domestic hot water, the input rate of radon (R) in picocuries per hour (pCi/hr) to a structure can be represented by the following equation:

$$R(pCi/hr) = Q \cdot K \cdot a \cdot C_{0.01} + W_d \cdot a \cdot C_{1.0}$$

Where:

Q - the NBSLD output of hourly heat load (BTU/hr) required to space heat a structure under designed climatic conditions.

K - a constant to convert BTU/hr to liters per hour of required hot water. The radiator and hot water systems were assumed to operate at an inlet water temperature of 82°C with a 8.3°C temperature loss across the heat exchangers. (K = 0.0309 liters/BTU)

a - the estimated partition factor or ratio of radon in air versus in water (0.01 for heat exchangers, 1.0 for pool and domestic uses).

W_d - the average volume of domestic hot water used per hour, (from Table 3).

C - the concentration of radon in the geothermal fluid, pCi/l.

The calculated radon input after an hour is subsequently reduced by ventilation and exponential decay (in Step three). This assumes that the ventilation make-up air contains only background concentrations of radon which cycles between 0.03 to 3.5 pCi/l daily (Johnson, et al., 1973). The resulting buildup of decay products (daughter isotopes of radon-222) are also affected by decay and ventilation processes. To remain conservative, "plate out" of the daughters was not considered. A computer program was developed from radon mass balance equations found in previous reports by Wilkening and Watkins, (1976) and Barton, et al., (1973). The program identified by the acronym, GEOWL1, is described in Appendix C.

The model was used to calculate a 24-hour working level profile for radon and its daughters that could be expected inside the enclosed buildings of the five applications under discussion in this report. Results were obtained to show the variation in the profiles with ventilation rates ranging from 0.5 to 4 air changes per hour (ACH). Appendix D summarizes these calculations.

DESCRIPTION OF NONELECTRICAL APPLICATIONS

Many geothermal fluids are currently exploited for space heating and for domestic hot water uses. In this report, five applications were chosen as being representative of such uses in the western United States. For each case, an example is believed to be available in the western United States to verify the dose model presented herein. The design parameters for the structural and climatic variables do not describe a particular known building but were compiled from a number of firsthand observations. The calculated radon working levels are intended to show the relative potential for exposure to radon daughters among the various uses.

At most of the observed uses, local geothermal resources were developed to compliment or even substitute other energy systems. It is apparent that low-temperature (below 160°C) geothermal reservoirs can be utilized for many uses. For instance, economic incentives and creative business attitudes have resulted in investments in agricultural uses including fish farming, vegetable and flower production, commercial processing of asphalt emulsions, milk pasteurization, snow melting and a unique business concern which casts plastic explosives (Garside, 1974). For these and other applications, minimum technical expertise was required but much experimentation and inventiveness is evident. The hot water (or low temperature steam) source such as artesian wells, springs, pools or fumaroles were tapped by various means to divert the fluid to a nearby structure. In some cases, the natural flow was insufficient to meet demand; therefore, pumps and deeper wells were required.

If reservoir temperatures up to 250°C were available, numerous industrial processes could be adapted to geothermal energy.

Reistad (1975) has compiled a table of various processes and the required temperature for potential geothermal reservoir developments. Of course, in order to produce reservoirs of high temperature water, sophisticated drilling and engineering techniques are needed.

For purposes of this report, the geothermal fluids available to provide space heating and domestic hot water for the applications are assumed to be only 82°C at the point of heat release. Thus these geothermal sources are simply a hot water system with no flashing (phase separation). Of course, the reservoir temperatures may be much higher.

Heat extraction methods observed during the sampling phase were dependent upon the chemical constituents of the geothermal fluids. Some of the fluids are corrosive (low pH) and present scaling problems (high mineralization). In these cases, primary interfaces or sacrifice systems are used to heat water or air which in turn is circulated to the heat exchangers. Such systems, being exposed to such fluid chemistry, are constructed to withstand the geothermal environment. For example, in Klamath Falls, Oregon, within-the-well heat exchangers or U-tube exchangers have been successfully used to minimize damage to sensitive plumbing within the structure. This method circulates domestic water through a pipe placed in the geothermal well, which subsequently flows to the radiators within the structure. The water is then recycled to the well for reheating. No geothermal water is withdrawn. This technique also minimizes waste and discharge problems (Peterson and Groh, 1967).

The following paragraphs briefly describe the nonelectrical applications to be evaluated in this report. These brief descriptions are derived mostly from the recollection of the authors but some references are provided for more detail. Until the energy crisis became evident in 1975, geothermal heat was neither

developed to its best and highest use nor was it always an economically competitive energy source. Therefore, many current applications are simple adaptations of existing technology at the least affordable cost. The development of future systems by individuals, corporations and public entities may extend this resource to new and broader applications not addressed in this report. Reistad (1975) has outlined such scenarios.

GREENHOUSES

Large Quonset type and rectangular "hot house" structures were observed near Susanville, California; Lakeview, Oregon; Wabuska, Nevada; and Willard, Utah. Recently, the Oregon Institute of Technology at Klamath Falls, Oregon designed and built a geothermally heated greenhouse to be used to investigate construction, engineering and efficiency (Karr and Laskin, 1977). The aforementioned observed structures are commercial ventures operated by individuals, families or partnerships. The buildings are made of wood or steel supporting frames with fiberglass or glass sheathing. The principal product of greenhouses has been tomatoes although at a noncommercial greenhouse, in Colorado, flowers were grown year round.

Hannah (1975) and Rosenbruch and Botige (1976) have reported in detail the costs and operational aspects of the well known Hobo Wells Hydroponics operation outside Susanville, California. In summary, the thermal water is pumped from a spring into a holding tank from which water is fed to a radiator. A fan is used to circulate the air within the structure via the radiator. Some of the spent or waste water leaving the greenhouse flows into a nutrient tank. The nutrient solution is used for flood irrigating within the greenhouse.

PRIVATE RESIDENCES

In Klamath Falls, Oregon; Reno, Nevada; Susanville, California; and Boise, Idaho, geothermal heat has been utilized in many homes for space heating requirements and domestic hot water supplies. In the majority of situations, each home has its own well. Very few community heating and hot water systems have been developed as in Iceland and Hungary. In Boise, Idaho there is a private district heating system which supplied geothermal water to nearly 400 homes at one time. Presently 200 homes are still utilizing this system (Hamilton, 1977).

Heat extraction, within a house, usually uses a system of pumps, thermostats, pressure regulators, storage or surge tanks to maintain flow, and either forced-air or gravity designed radiators. The thermal ground water is pumped through this system, a portion of the heat extracted, and the "waste" water is discharged to open drainages or reinjected. As previously mentioned, the corrosiveness and scaling potential of some geothermal waters in Klamath Falls, Oregon prohibits it from being distributed through the rather "delicate household systems." At these locations a U-tube heat exchanger is placed within the well such that city water can be heated and circulated between the well exchanger and those within the structure (Peterson and Groh, 1967).

In some cases (i.e., Reno), the thermal groundwater does not contain noxious odors or tastes and also conforms to State and Federal water supply standards for private wells. This well water is not only used for space heating but also for domestic purposes. In the case of shallow thermal wells in the Imperial Valley of California, however, the hot water is high in total dissolved solids and alkalinity. This water is normally used solely for non-potable uses such as bathing and dishwashing. However, it was observed that in some cases the migrant farm labor force in that area may also use this water as a potable water supply (O'Connell and Kaufmann, 1976).

MOTELS AND APARTMENT COMPLEXES

At two motels and one apartment complex in Reno, Nevada, space heating and domestic potable water are provided by geothermal wells (O'Connell, Kaufmann, 1976). Space heating of these structures is similar to that of a conventionally heated structure using either baseboard floor heaters or a central heating design. Recently, in Klamath Falls, Oregon a complex of four (4) two story four-plexes have been built (Lund, 1977). The complex utilizes individual forced-air heat exchangers such that new geothermal water is only added to the circulating system when the temperature of the system dips below a predetermined level. The "used" water is released to a storm drain.

A typical heating system for such a large structure requires the hot well water to be pumped to a central storage tank and then recirculated to each unit. This provides for controlled temperature distribution and less thermal waste.

SPAS AND RECREATIONAL FACILITIES

Perhaps the earliest record of the use of geothermal resources is the development of bathing communes and resorts around natural emanations. People of ancient Greece, the Roman Empire, Israel, Babylonia and other cultures developed and embraced the use of mineral spring areas (Horvath and Chaffin, 1971).

Many of the locations sampled during 1974-1975, were either active, business ventures or abandoned historical relics of early attempts (O'Connell and Kaufmann, 1976). .Commonly found at these facilities are large swimming pools (enclosed if in a cold climate), sauna rooms and hot whirl-pool type baths. "Vapor caves" were also observed in Colorado which were simply manmade caverns having hot spring water seeping out of the surrounding rock. Peterson (1976) has reported that 250 hot and mineral spring enterprises are currently operating in the United States.

STRUCTURAL DESIGNS AND EXPOSURE PATHWAYS

Five different structural designs are under consideration. They are: 1) a single story private home, 2) a single story motel, 3) a two story apartment building, 4) a glass greenhouse, and 5) an indoor swimming pool. Examples of these structures were observed during field sampling exercise. Also, Hannah (1975) and quarterly bulletins from the Geo-Heat Utilization Center at the Oregon Institute of Technology describe these and many other specific nonelectrical applications.

Tables 1, 2 and 3 provide a summary of pertinent input data for the National Bureau of Standards Load Design (NBSLD) computer program. This program is described in appendix A. The output obtained from this program is a daily profile of hourly heat requirements (BTUH) to balance structural and occupational heat losses. This heat is provided solely by the geothermal fluid. For the subsequent calculations of radon release, it is assumed that the hot geothermal water is circulated within the structure and not reheated, but reinjected or released to surface drains.

The Environmental Protection Agency feels that the primary exposure pathway to occupants of these structures is inhalation of radon daughters from the decay of radon released to occupied

TABLE 1. DESIGN DAY PARAMETERS

Maximum outdoor temperature	-6°C (21°F)
Daily range of outdoor temperature	17°C (10°F)
Design outdoor temperature	-23°C (10°F)
Ground heat transfer coefficient	0.6 BTUH/m^2/°C
Outdoor relative humidity	50%

TABLE 2. OBSERVED STRUCTURAL DESIGNS OF BUILDINGS GEOTHERMALLY SPACE HEATED

STRUCTURE	DIMENSIONS, meters	DESCRIPTION	EXTERIOR WALL COEFFICIENTS Transmission/Solar Absorption BTU per (hour)·(meter^2)·(°C)	
Greenhouse	18.2 x 12.2 x 3.6	A light frame structure constructed solely of 1/4" single pane glass	2.2	0
Apartment Buildng	30.4 x 9.1 x 5.2	A two story concrete block structure with interior gypsum board walls. The building is divided into ten-27.7m^2 units. Each unit has 8.9m^2 of 1/4" single pane glass	2.24	13.44
Motel	9.21 x 6.1 x 2.6	A single story concrete block structure with interior gypsum board walls. The building is divided into twenty-27.7m^2 units with 2.2m^2 of 1/4" single pane glass per unit	2.24	13.44
Indoor Pool Pool size	28.9 x 15.2 x 4.6 22.8 x 9.1 x 2.1	A concrete block structure with 35.7m^2 of 1/4" single pane glass	6.04	9.74
Private Residence Garage	19.4 x 7.6 x 3 5.5 x 4.6 x 3	A wood frame structure with exterior stucco finish and interior of gypsum board. The garage is heated. There are 15.6m^2 of double pane window glass.	6.04	9.74

TABLE 3. INTERNAL LOADS OF THE BUILDINGS AFFECTING HEAT LOAD AND OTHER WATER USAGE

STRUCTURE	INSIDE TEMP. °C	LIGHTING LOAD watts/m^2	OCCUPANCY persons/time intervals		DOMESTIC WATER USAGE (Eng. Manual, 1959) liters per hour
Greenhouse	24	43 (continuous)	4	0900-1700	0
Apartment Building	24	10 (occupied)	35	1700-0800	94
Motel	24	10 (occupied)	30	1700-0800	189
Pool	21 (night) 24 (day)	21.5 (occupied)	30	0900-1800	1135 (shower) 915 (pool makeup)
Private Residence	24	10.7 (occupied)	4	1700-0900 (over night)	22

areas. The secondary route is direct consumption of radon laden water. The source of radon within the structure is the radiator, associated plumbing and venting.

The air-water ratio between the radon content in the incoming fluid and content in the air is defined as a partition fraction. This factor varies according to the use and the heat transfer for technology. For this report, partition fractions are estimated.

The domestic water usages in Table 3 are expected volumes of radon laden hot water that will release dissolved radon at the time of use. In recreational situations, i.e., saunas and pools, radon will be released as the thermal water is replenished and circulated. Daily water usage within the greenhouse was assumed to be zero since mixing of nutrients in the holding tank before irrigation will probably reduce the radon concentration significantly and therefore, not contribute to the radon buildup in the structure. Therefore, flood irrigation of the greenhouse is assumed not to be a source of radon. The other domestic uses are primarily bathing and washing.

RADON IN THERMAL WATERS

Radon content of hot springs and other geothermal systems (well, pools, etc.) have been reported worldwide. Observed concentrations have shown that at many locations, radon will vary considerably even within local or regional settings. This variation has been attributed either to seismic activity (Craig, et al., 1975), regional geology (Jurain, 1960), or cold water intrusion (Mazor, et al., 1973). As of yet, there is no exact correlation of radon to any natural event or situation that enables one to predict radon concentration in groundwater other than to note that its presence can be expected. It has also been found that radon in producing geothermal zones will vary with time and production volumes (Stoker and Kruger, 1975). In Table 4, radon concentrations in thermal systems observed worldwide are summarized.

TABLE 4. WORLDWIDE OBSERVATIONS OF RADON-222 CONCENTRATIONS IN THERMAL WATERS

Location	Rn-222 Pico Curies*/Liter	Reference Source
Badgastein, Austria (1972)	500 - 120,000	Pohl-Ruling
Bath, England	23,000 (average)	Andrews and Wood (1974)
Taupo Graben, New Zealand	800 - 320,000	Belin (1959)
Hammat Gader, Israel (1973)	2,900 - 7,420	Mazor, et al.,
Japan	29,000	Moringa (1958)
Kamchatka, USSR	1,000 (fumaroles)	Cherdynstev
Hot Springs, National Park, Arkansas, USA	30,500	Kuroda, et al., (1954)
Western USA	3 - 14,000	O'Connell and Kaufmann (1976)

*10^{-12} curies

It should be noted that elevated radon concentrations in geothermal waters are sometimes within concentration ranges typical of cold water sources. Pohl-Rüling (1972) found radon in cold springs in the Badgastein, Austria region to vary from 100-36,000 pCi/l. In the United States, a review of available ground water data (438 samples) found that 74 percent contained radon concentrations up to 2000 pCi/l and of the remaining 26 percent, five percent were above 10,000 pCi/l (USEPA, 1977). In Maine and New Hampshire, a U.S. Public Health Service study (Grune et al., 1960) reported that of the nearly 250 cold water wells sampled, radon concentrations exceeded 10,000 pCi/l for 24 percent of the locations and 100,000 pCi/l for 2 percent.

From the previous study of low-temperature (<100°C) geothermal fluids in the western United States, O'Connell and Kaufmann (1976) measured radon concentrations up to 14,000 pCi/l. This particular location was an artesian well located near the San Andreas fault in Southern California. It has been developed to supply a recreational spa complex with hot water for pools and saunas. In Table 5, a summary of observed radon concentrations throughout the western United States are presented to clarify the various uses. They are: hydroponic applications which include hothouse and greenhouse uses, indoor/outdoor pools and saunas were usually recreational facilities; and potable water supplies because at some locales the thermal water met state drinking water standards, although in most areas, high hydrogen sulphide concentrations or dissolved solids content limited the hot water usage to either bathing, dishwashing, or space heating.

Radon data from the previous report (O'Connell and Kaufmann, 1976) are grouped into categories (Table 5) (as shown by the horizontal lines). The average radon concentrations are calculated from observed radon values. The combined averages (in Table 5) are calculated from grouping similar uses. It was felt that the combined averages were more appropriate to use in the calculations since multiple uses were observed at many developments.

TABLE 5. RANGE OF RADON-222 CONCENTRATIONS FOUND IN THERMAL WATERS IN THE WESTERN US[1]

Uses	Number of Observed Locations	Range of Dissolved Radon-222 in Water pCi/l	Observed Average pCi/l	Combined Average pCi/l
Hydroponics	3	32 - 1,400	564	564
Indoor Pools	6	13 - 5,800	1,369	2,231
Outdoor Pools	18	72 - 14,000	2,432	
Saunas	18	61 - 14,000	2,319	
Potable Water	7	58 - 980	365	365
Non-Potable Water	5	120 - 2,100	778	490
Heat Exchanger	11	58 - 1,400	360	

[1]From O'Connell and Kaufmann, 1976

In Table 6, a summary of the radon concentrations from Table 5 is presented whose combined use approximates the five design applications discussed in this report.

TABLE 6. RADON-222 CONCENTRATIONS ASSUMED TO BE TYPICAL OF VARIOUS APPLICATIONS OF GEOTHERMAL WATERS

STRUCTURE	pCi/l
Greenhouse	564
Apartment Building	365
Motel	365
Private Residence	490
Indoor Pool	2231

RESULTS

The concept of the model described below is based upon standard engineering guides, a mass balance methodology and a few critical assumptions. The results are working levels (WL) of radon and its daughters, (polonium-218, lead-214, and bismuth-214) inside the predescribed structures. The few critical areas which affect the calculated working levels and more importantly, future verification of these concentrations are:

(1) that the design day conditions are considered typical winter conditions,

(2) that radon is degassed inside the house and can be described as a percentage of the total radon flowing hourly through the system,

(3) that structural heating and ventilation parameters are adequate,

(4) that radon daughter "plate out" is not significant, and,

(5) that higher than calculated WL's may be expected in enclosed rooms where large quantities of water are used and ventilation is minimal such as the laundry or bath.

THE COMPUTER PROGRAMS

The computational sequence and input parameters of the computer programs are shown in Figure 2. To accommodate variations in ventilation rates, structural design and radon in water

concentrations, these parameters remained as input variables for each application whereas heat exchanger efficiencies, radon air/water ratios, ambient radon concentration and climatic conditions remained integrated into the calculations. The calculation scheme is depicted as follows:

OUTPUT	Btu/hr	atoms/hr of radon	Hourly WL's
PROGRAM	NBSLD (Appendix A)	Heat Exchanger Conversion (Appendix B)	GEOWLI (Appendix C)
INPUT	Structural Design Ventilation rates	Radon in water conc.	Ventilation rates

Figure 2. Variables required to calculate working levels inside geothermal heated structures using constant radon partition functions and climatic data

Working levels (WL) are computed on an hourly basis for a 24-hour cycle or a complete day. The program, GEOWL1, has the capability of continuous operation for multiple day buildup. It is noted however, that after the first day (24-hour period) the subsequent hourly profiles are repeated if the same hourly radon input and structural ventilation rates are used.

WORKING LEVEL CONCENTRATIONS

Appendix D contains a summary of calculated working level concentrations for the previously described structures. The output is dependent upon ventilation rate changes. In Table 7, the maximum calculated working level concentrations are summarized for potentially occupied time periods (see Table 3). These are not necessarily the highest values calculated. In general, space heating requirements are the highest in the early morning hours (1-5 a.m.) and subsequently also the maximum working level concentrations. Since greenhouses are not occupied during those hours,

the maximum reported in Table 7 is not the daily maximum from Appendix D. In the case of an indoor swimming pool, the air temperature was allowed to drop 3°C at night. Therefore, as shown in Appendix D, the peak heat use (and working levels) for greenhouses and pools occurs during the occupied period.

TABLE 7. MAXIMUM WORKING LEVELS FOR THE DESIGN STRUCTURES DURING OCCUPATION ($x10^{-3}$)

STRUCTURE	AIR CHANGES PER HOUR				
	0.5	1.0	2.0	3.0	4.0
Greenhouse	1.18*	0.94	0.79	0.77	0.70
Apartment Bldg	1.36	1.02	0.83	0.76	0.72
Motel	1.69	1.14	0.87	0.78	0.73
Indoor Pool	29.96	9.58	3.21	1.89	1.4
Private Residence	1.46	1.08	0.86	0.77	0.73

*i.e., 1.18×10^{-3}

To estimate the potential lung dose from exposure to the radon-222 daughters represented by the working levels shown in Table 7, requires the selection of a dose conversion factor. Johnson, et al., (1973) in their work on radon daughter exposures from natural gas, identified and acknowledged the wide variation found in the literature. They found that the important reasons that dose conversion factors were not inter-comparable are that "each exposure situation has involved different radon - daughter equilibrium conditions, free ion fractions and carrier particle sizes for attached daughters."

DOSE CONVERSION

Barton, et al., (1973) used a dose conversion factor of 100 rads per year to the lungs for a continuous exposure at one working level (100 pCi/l of radon in secular equilibrium with daughters) and a quality factor of 10. Computations of radon and daughters using GEOWL1 show that such equilibrium is not obtained under the conditions selected for this report. Duncan, et al.,

(1976) used a dose conversion factor based upon a radon daughter equilibrium ratio of 1:0.9:0.5:0.35. They computed that 0.25 working level months/year (WLM/YR) is equal to a maximum dose of 4 Rem/year in the 5th generation bronchus of the lungs.

The aforementioned dose conversion factors may not be adequate to describe expected doses from short term (winter months only) exposures resulting from space heating since they were developed using continuous inhalation models. In the case of enclosed swimming pools and greenhouses, they may apply for continuous users or workers. Even though 50 percent equilibrium was not computed, the dose conversion factor 0.25 WLM/Yr was used to develop Table 8. Because the potential for exposure from geothermal space heating systems is highest during four winter months, the WL's calculated for homes, apartments and motels are for this time period. The greenhouse and pool applications use water year round, therefore, the working levels calculated for the worst case situation are assumed to hold for 12 months. Using the calculated working levels in Table 7, annual doses were derived and summarized in Table 8.

TABLE 8. POTENTIAL DOSES FROM INHALATION OF RADON DAUGHTERS IN STRUCTURES UTILIZING GEOTHERMAL HEAT, REM/YR

STRUCTURE	AIR CHANGES PER HOUR				
	0.5	1.0	2.0	3.0	4.0
Greenhouse	0.94	0.75	0.63	0.61	0.56
Apartment Bldg	0.36	0.26	0.21	0.19	0.19
Motel	0.45	0.30	0.29	0.20	0.19
Indoor Pool	23.94	7.60	2.50	1.50	1.12
Private Residence	0.38	0.28	0.23	0.20	0.19

Note: The dose contribution from the domestic hot water uses during the non-winter seasons for the apartment motel, and house were not included since the maximum WL's in Table 7 showed little contribution from this source of radon.

CONSUMPTION DOSE

The consumption of geothermal fluids is not common place since there are many instances of obnoxious tastes and odors. However, in the Soviet Union, it is reported that there are 86 mineral water bottling plants presently in operation (Informatics, 1972). According to this same report, the Soviets have set a norm of 5000 pCi/l of radon for thermal waters to be considered for balneological use. In the United States there are a few places which also produce a bottled product for general consumption. These products are available in food stores and markets nationwide. Data is not presently available as to the radium concentration in these waters and the subsequent radon buildup inside the containers.

From the previous report, the observed average radon-222 concentration for potable (drinkable) waters is 365 pCi/l (Table 5). Since there are cases of intentional drinking of mineral water at health clinics and spas and also routine consumption of potable hot water supplies (i.e., in Reno, Nevada), an estimate of potential exposures is warranted. The critical organ is the stomach. The dose equivalent was reported by Suomela and Kahlos (1972) to range from 350 to 380 mrem/μCi ingested. A worst case estimate, assuming a daily intake of 2000 ml of raw non-boiled water, yields a consumption dose of approximately 100 mrem/yr.

CONCLUSIONS

Five applications of nonelectrical uses of geothermal energy resources were evaluated for potential doses from the inhalation and/or consumption of radon-222. These uses include spaceheating, domestic hot water sources, and recreational examples which were observed during a previous field sampling survey (O'Connell and Kaufmann, 1976).

The maximum calculated working levels for each application are summarized in Table 7. These concentrations are expected values during occupied periods. The annual inhalation dose to individuals resulting from a four month exposure period (winter conditions at design day conditions) to the maximum concentrations are presented in Table 8. The contribution of radon-222 to the inside air from the spaceheating model greatly exceeded that from domestic hot water uses, therefore Table 8 contains accumulated doses from those months of maximum spaceheat demand for the apartment, motel and private residence applications. The greenhouse and indoor pool examples are expected to withdraw hot water from the geothermal reservoir year round but at reduced volume. In some circumstances, the hot water well must be kept flowing to prevent the well from "cooling down" and stopping artesian flow. Elsewhere, at many recreational spas, there is little or no control of the incoming water because the source (spring or well) is connected directly to the mineral baths or saunas. Therefore, for these applications, the expected doses shown in Table 8, were calculated using the maximum working levels for year round exposure periods.

Ingestion doses to the stomach were calculated from the annual consumption of domestic water, all of which originated

from the geothermal source. Even though in most cases, cold water supplies are more likely to be used, there are circumstances where for balneological reasons, mineral water is consumed. A dose of 100 mrem/yr was calculated using a known radon-222 concentration (365 pCi/l) for a potable geothermal source.

The highest working levels and resulting lung doses were calculated for an indoor pool. The degassing of radon from pool water into a poorly ventilated building may produce significant airborne concentrations. Though radon is nearly ten times more soluble in water than oxygen from 0 to 70°C (Lawrence, et al., 1946), agitation from recirculation and use will release much of the radon. The employees and repetitious users of such a facility may accumulate long exposure periods.

At the present time specific criteria are not available to provide guidance as to what levels are advisable for homes or commercial establishments having the potential to accumulate radon-222 and subsequently its daughters from building materials, natural gas or geothermal resources (all of which are sources of radon-222). There are recommendations and criteria coupled with remedial measures for homes and other buildings which have been built using uranium mill tailings for structural foundations (e.g., in Grand Junction, Colorado) or have been built on reclaimed phosphate strip mines in Florida. The U.S. Surgeon General's Guidelines recommend remedial action above 0.05 WL of indoor radon daughter products for dwellings constructed on or with uranium mill tailings. In Canada, recently, it was announced that 0.02WL is the primary criterion above which remedial action will be necessary to limit radon-222 build up in homes built on uranium mill wastes (from a news release on behalf of the Federal Provincial Task Force on Radioactivity, Atomic Energy Control Board, April 7, 1977). Recently, the United States Environmental Protection Agency recommended 0.005 WL as the upper level for new habitable structures built on reclaimed phosphate land.

As shown in Appendix D, the calculated WL's are inversely related to the ventilation rate. Reduction in the working level concentrations are particularly noteworthy for the indoor pool circumstance where doubling of the ventilation rate can reduce the working level value by up to 60%. For the other structures, the change in working level is less dramatic with average reductions of 19-25% being calculated where the ventilation rate is doubled.

It was found that at the maximum concentration conditions (ACH=0.5) for any of the structures, the radon daughter build up would not produce a working level concentration exceeding the Surgeon General's 0.05 WL guideline if the combined average radon-222 concentrations in water for known geothermal systems were used. In some actual cases or locations, the guidelines would be exceeded if a higher activity radon source was present or if ventilation and other design parameters were not similar to those assumed in this report. It is shown that the EPA guidelines of 0.005 WL were not exceeded in any example structure if the ventilation rates were 2 ACH or greater. At some recreational facilities, where radon-222 concentrations in water were as high as 14,000 pCi/l, the ventilation rates would have to be much higher not to exceed this guideline.

Since there is uncertainty in the proposed model, particularly the radon air/water partition fraction for heat exchangers and degassing pool water, there is an obvious need for verification studies. These efforts should be conducted at existing structures with known radon input rates (calculated or estimated) to verify the effect of ventilation especially in limiting circumstances such as saunas or steam rooms where ventilation is undesirable. Since increased ventilation produces a corresponding higher radon input rate (replacement of lost heat causes higher flow rates from the geothermal reservoir), optimization of competing requirements may be desirable for those structures found to contain high working level values.

Geothermal energy can be utilized for nonelectrical applications of space heating and hot water supplies without radiological health implications by using engineering techniques to either remove radon from the heating system or to contain it within the system. Recreational or balneological uses of thermal or mineral waters present more difficult problems, yet in many cases radon and other minerals and gases are considered desirable constituents.

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APPENDIX A

NBSLD, THE COMPUTER PROGRAM FOR CALCULATING HEATING AND COOLING LOADS IN BUILDINGS

NBSLD, the National Bureau of Standards Load Determination program is a compilation of various algorithms and subroutines recommended by the American Society of Heating, Refrigeration and Air Conditioning Engineers Task Force Group on Energy Requirements. The program is very extensive and contains, within the subroutines, thermal resistance data for many materials.

Kusuda (1976) describes the energy balance equations that depict the amount of energy transferred from and simultaneously added to a room at any time. Wehlage (1976) and Olivieri (1973), in their books on design, have outlined and presented examples of heat transfer through exterior structural surfaces. The fundamental heat transfer equation which describes heat (energy) conduction through a medium is:

where: $Q = A(u)(\Delta T)$

A = surface area, ft^2

u = coefficient of transmission, BTU/hr ft^2 °F

ΔT = temperature differential of media, °F

Q calculates to be, in english units, BTU/hr (BTUH). Thermal resistances (R) are reported for various construction materials by the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE, 1972). The coefficient of transmission is related to R as:

$$u = 1/R$$

For building material of multiple layer construction an overall coefficient of transmission is computed from:

$$u = \left(\sum_{1}^{m} R_m\right)^{-1} \quad \text{where } m = \text{number of layers}$$

In applications involving four walls, a roof, a floor, interior ceiling, windows, doors, and infiltration of outside air, the calculations become quite lengthy. Complications arise from internal energy sources, solar loading, exterior shading, and thermal storage effects of the building. The resulting computations are not practical for every day usage. Therefore, many architects result to standard "rules of thumb" which have been developed for various climatic conditions. This may result in over design for heating and cooling equipment.

Since geothermal application are using resources of possibly marginal temperatures, and are faced with restrictions on disposal of waste water, and withdrawal of groundwater, it was felt that through the use of this computer program, the calculations could be performed for any structure with adequate accuracy to optimize resource utilization. The program, NBSLD, developed by the National Bureau of Standards Center for Building Technology was the first program of its kind to be available. Since 1976, others have been developed at the University of California, Berkeley and the U.S. Army Civil Engineering Laboratory, Champaign, Illinois (Barnett, 1977).

The output from this program is a 24-hour profile of hourly energy requirements. For purposes of this study, the design characteristics found in Tables 1-3 were used to compute the profiles for the 5 structures. The ventilation rate was varied from 0.5 to 4 ACH to compute the increased heating load that would be required to maintain similar interior conditions. The hourly WL profiles are shown as a function of ventilation rate in Appendix D.

APPENDIX B

CONVERSION OF BTU/HR TO RADON INPUT RATE, ATOMS/HR

A data processing program was written in BASIC language to be used with a Hewlett Packard model 9830 programmable calculator. The program converts the heat load data from NBSLD plus domestic water usuage and/or pool makeup water requirements, to an hourly radon-222 input rate. This program assumes the following:

(1) the temperature drop across the heat exchangers for space heating is 8.3°C (15°F),

(2) space heating needs for each case except for the indoor pool (pool water losses provide significant heat input) is provided by the heat exchangers only, and

(3) the radon air/water heat exchanger partition fraction is 0.01.

The basic relationship describing heat release from a radiator with heat supplied by a fluid medium (Grinnell, 1969) is:

Heat transferred = Flow rate x fluid density x specific heat x temperature change

The system flow rate (liters per hour) is calculated from the above equation. The fraction of radon-222 release inside the structures (assumed to be 0.01) is used to estimate, from the average radon in water concentrations, the radon input rate (atoms/hr).

The hourly radon input rate from space heating sources is adjusted by the additional releases from the domestic and/or pool water sources, assuming that 100% of the dissolved radon from these uses are released to the interior air.

APPENDIX C

GEOWL1
A PROGRAM TO COMPUTE WORKING LEVELS OF RADON-222 AND DAUGHTER IN STRUCTURES

The purpose of the GEOWL1 program and its associated subroutines is to calculate the number of atoms of radon-222 and its first three daughters (Po-218, Pb-214, Bi-214) in a room under the following conditions:

1) Radon enters and disperses on a continuous basis but the input rate will vary hourly, as a function of heating requirements

2) there is an exchange of air volume with outside air, (i.e., known ventilation rate)

3) the air being exhausted (from ventilation) contains the same concentration of radon daughters as the room air (i.e., assume complete mixing),

4) the incoming air (from ventilation) contains background levels of radon and daughters. (Note: A background concentration for radon-222 was assumed to be 0.1 pCi/l, and the daughters were assumed to be in the ratio 1./0.6/0.5).

Working levels are calculated as described by Evans (1969) coupled with a mass balance equation to account for the buildup, ventilation losses and radioactive decay of radon-222 and daughters. This mass balance is represented as:

$$\frac{d[\text{Radon}]}{dt} = \text{Radon}_{\text{input}} - \text{Radon}_{\text{out}} - \text{Radon}_{\text{decay}}$$

Similar forms for subsequent radon daughters can be written except that the input terms are provided by the decay of the preceding isotope.

The radon mass balance equation can be written as:

$$\frac{dA}{dt} = \underbrace{A_{BTU} + A_{Bkgd}V}_{in} - \underbrace{A\,F - A\lambda_a}_{out}$$

Where A_{BTU} = Radon input from heat exchangers, atoms/hour

A_{Bkgd} = Radon background concentration, atoms/liter

V = Ventilation rate, liters/hour

A = Total radon concentration inside structure, atoms

F = Fraction of room (air) volume removed by ventilation, air changes per hour

λ_a = Radon decay constant, $hour^{-1}$

Rearranging this equation yields:

$$\frac{dA}{dt} + \lambda_a \cdot A + A \cdot F = A_{Bkgd} \cdot V + A_{BTU} \quad \text{or}$$

$$\frac{dA}{dt} + A(\lambda_a + F) = A_{Bkdg}V + A_{BTU}$$

This expression and subsequent expressions for the radon daughters take the form of a linear differential equation:

$$\frac{dy}{dx} + P(x)Y = Q(x)$$

which has an integrating factor of the form:

$$e^{\int P(x)\,dx}$$

which yields a solution of the form (Ross, 1974):

$$Y = e^{-\int P(x)dx}\left[\int e^{\int P(x)dx} Q(x)dx + c\right]$$

Using this solution, the differential describing radon-222 concentration at time, t, is:

$$A = A_k + (A_o - A_k)e^{-t(\lambda_a + F)} \qquad \text{where:}$$

$$A_k = \frac{A_{Bkgd} \cdot V + A_{BTU}}{(\lambda_A + F)}$$

A_o = Radon at t = o, a constant assumed to equal ambient air concentrations.

Similar computations are necessary for the radon daughters Po-218, Pb-214 and Bi-214. Solutions to the linear differential equation 2, are lengthy and will not be presented here. GEOWL1 incorporates these solutions to produce a 24 hour profile of the number of atoms present inside the buildings. Working levels are calculated for midpoint of each hour using the method described by Evans (1969).

This program utilizes a CDC-6400 computer which computes the parental decay, the subsequent ingrowth of daughters, the losses due to ventilation all on a repetitious time scale of one second. The number of atoms of radon and its daughters are continuously summed. The program does not account for losses of radon daughters from free ion attraction to dust and subsequent deposition nor plating out on wall surfaces.

APPENDIX D

WORKING LEVELS FOR THE 5 DESIGN STRUCTURES USING DIFFERENT VENTILATION RATES

SUMMARY OF WORKING LEVELS ($\times 10^{-3}$) CALCULATED FOR A GREENHOUSE USING GEOTHERMAL WATERS CONTAINING 564 pCi/l RADON-222

HOUR	AIR CHANGES PER HOUR				
	0.5	1.0	2.0	3.0	4.0
1	1.16*	0.95	0.80	0.78	0.71
2	1.17	0.96	0.80	0.78	0.71
3	1.19	0.96	0.80	0.78	0.71
4	1.19	0.96	0.81	0.78	0.71
5	1.20	0.96	0.81	0.78	0.71
6	1.20	0.96	0.81	0.78	0.71
7	1.20	0.96	0.81	0.78	0.71
8	1.18	0.94	0.79	0.77	0.70
9	1.16	0.93	0.79	0.77	0.70
10	1.14	0.93	0.79	0.76	0.70
11	1.13	0.92	0.78	0.76	0.70
12 (noon)	1.11	0.91	0.78	0.75	0.70
13	1.09	0.90	0.77	0.75	0.70
14	1.07	0.89	0.77	0.75	0.70
15	1.06	0.89	0.77	0.75	0.69
16	1.05	0.88	0.77	0.75	0.69
17	1.07	0.90	0.79	0.76	0.70
18	1.09	0.91	0.79	0.76	0.70
19	1.10	0.92	0.79	0.77	0.70
20	1.11	0.92	0.79	0.77	0.70
21	1.12	0.93	0.79	0.77	0.71
22	1.13	0.93	0.80	0.77	0.71
23	1.14	0.94	0.80	0.77	0.71
24	1.15	0.95	0.80	0.78	0.71

*i.e., 1.16×10^{-3} WL

SUMMARY OF WORKING LEVELS ($\times 10^{-3}$) CALCULATED FOR AN APARTMENT BUILDING USING GEOTHERMAL WATERS CONTAINING 360 pCi/l RADON-222

HOUR	AIR CHANGES PER HOUR				
	0.5	1.0	2.0	3.0	4.0
1	1.34*	1.02	0.82	0.75	0.72
2	1.35	1.02	0.83	0.75	0.72
3	1.35	1.02	0.83	0.76	0.72
4	1.35	1.02	0.83	0.76	0.72
5	1.36	1.02	0.83	0.76	0.72
6	1.36	1.02	0.83	0.76	0.72
7	1.36	1.02	0.83	0.76	0.72
8	1.36	1.02	0.82	0.76	0.72
9	1.36	1.02	0.82	0.75	0.71
10	1.35	1.01	0.82	0.75	0.71
11	1.34	1.00	0.81	0.75	0.71
12 (noon)	1.33	0.99	0.81	0.74	0.71
13	1.31	0.99	0.81	0.74	0.71
14	1.31	0.98	0.81	0.74	0.71
15	1.30	0.98	0.81	0.74	0.71
16	1.31	0.99	0.81	0.74	0.71
17	1.31	0.99	0.81	0.74	0.71
18	1.31	0.99	0.81	0.74	0.71
19	1.31	0.99	0.81	0.74	0.71
20	1.31	0.99	0.82	0.75	0.71
21	1.32	1.00	0.82	0.75	0.71
22	1.33	1.00	0.82	0.75	0.71
23	1.33	1.01	0.82	0.75	0.71
24	1.34	1.01	0.82	0.75	0.72

*i.e., 1.34×10^{-3} WL

SUMMARY OF WORKING LEVELS ($\times 10^{-3}$) CALCULATED FOR A MOTEL USING GEOTHERMAL WATERS CONTAINING 360 pCi/l RADON-222

HOUR	AIR CHANGES PER HOUR				
	0.5	1.0	2.0	3.0	4.0
1	1.67*	1.14	0.87	0.77	0.73
2	1.67	1.14	0.87	0.78	0.73
3	1.68	1.14	0.87	0.78	0.73
4	1.69	1.14	0.87	0.78	0.73
5	1.69	1.14	0.87	0.78	0.73
6	1.69	1.14	0.87	0.78	0.73
7	1.69	1.14	0.87	0.78	0.73
8	1.69	1.14	0.87	0.77	0.73
9	1.69	1.14	0.87	0.77	0.73
10	1.68	1.13	0.86	0.77	0.73
11	1.67	1.13	0.86	0.77	0.72
12 (noon)	1.66	1.12	0.85	0.76	0.72
13	1.65	1.11	0.85	0.75	0.72
14	1.64	1.11	0.85	0.76	0.72
15	1.64	1.11	0.85	0.76	0.72
16	1.64	1.11	0.85	0.76	0.72
17	1.64	1.11	0.85	0.76	0.72
18	1.64	1.11	0.85	0.76	0.72
19	1.64	1.12	0.85	0.77	0.72
20	1.64	1.12	0.86	0.77	0.72
21	1.65	1.12	0.86	0.77	0.73
22	1.66	1.13	0.86	0.77	0.73
23	1.66	1.13	0.86	0.77	0.73
24	1.67	1.13	0.87	0.77	0.73

*i.e., 1.67×10^{-3} WL

SUMMARY OF WORKING LEVELS ($\times 10^{-3}$) CALCULATED FOR A PRIVATE RESIDENCE USING GEOTHERMAL WATERS CONTAINING 490 pCi/l RADON-222

HOUR	AIR CHANGES PER HOUR				
	0.5	1.0	2.0	3.0	4.0
1	1.44*	1.07	0.85	0.77	0.73
2	1.45	1.07	0.86	0.77	0.73
3	1.45	1.08	0.86	0.77	0.73
4	1.45	1.08	0.86	0.77	0.73
5	1.46	1.08	0.86	0.77	0.73
6	1.46	1.08	0.86	0.77	0.73
7	1.46	1.08	0.86	0.77	0.73
8	1.46	1.07	0.86	0.77	0.73
9	1.45	1.07	0.85	0.77	0.73
10	1.44	1.06	0.85	0.76	0.73
11	1.43	1.05	0.84	0.76	0.72
12 (noon)	1.41	1.04	0.83	0.76	0.72
13	1.40	1.03	0.83	0.76	0.72
14	1.39	1.03	0.82	0.76	0.72
15	1.39	1.02	0.82	0.76	0.72
16	1.39	1.03	0.83	0.76	0.72
17	1.39	1.03	0.83	0.76	0.72
18	1.38	1.03	0.83	0.76	0.72
19	1.39	1.04	0.84	0.76	0.72
20	1.39	1.04	0.84	0.74	0.73
21	1.40	1.05	0.84	0.76	0.73
22	1.41	1.06	0.85	0.77	0.73
23	1.42	1.06	0.85	0.77	0.73
24	1.43	1.07	0.85	0.77	0.73

*i.e., 1.44×10^{-3} WL

SUMMARY OF WORKING LEVELS ($\times 10^{-3}$) CALCULATED FOR AN INDOOR POOL USING GEOTHERMAL WATERS CONTAINING 2231 pCi/l RADON-222

HOUR	AIR CHANGES PER HOUR				
	0.5	1.0	2.0	3.0	4.0
1	14.26 *	5.85	2.62	1.74	1.36
2	14.16	5.85	2.62	1.74	1.36
3	14.11	5.85	2.62	1.74	1.36
4	14.07	5.85	2.62	1.74	1.36
5	14.05	5.85	2.62	1.74	1.36
6	14.04	5.85	2.62	1.74	1.36
7	14.03	5.85	2.62	1.74	1.36
8	14.03	5.85	2.62	1.74	1.36
9	17.47	8.42	3.98	2.66	1.97
10	22.05	10.62	4.48	2.80	2.01
11	25.27	11.57	4.56	2.81	2.01
12 (noon)	27.29	11.94	4.57	2.81	2.01
13	28.51	12.07	4.58	2.81	2.01
14	29.25	12.12	4.58	2.81	2.01
15	29.69	12.14	4.58	2.81	2.01
16	29.96	12.14	4.58	2.81	2.01
17	26.68	9.58	3.21	1.89	1.4
18	22.19	7.37	2.71	1.75	1.36
19	19.02	6.43	2.63	1.74	1.36
20	17.04	6.07	2.62	1.74	1.36
21	15.84	5.93	2.62	1.74	1.36
22	15.12	5.88	2.62	1.74	1.36
23	14.68	5.87	2.62	1.74	1.36
24	14.42	5.86	2.62	1.74	1.36

*i.e., 14.26×10^{-3} WL